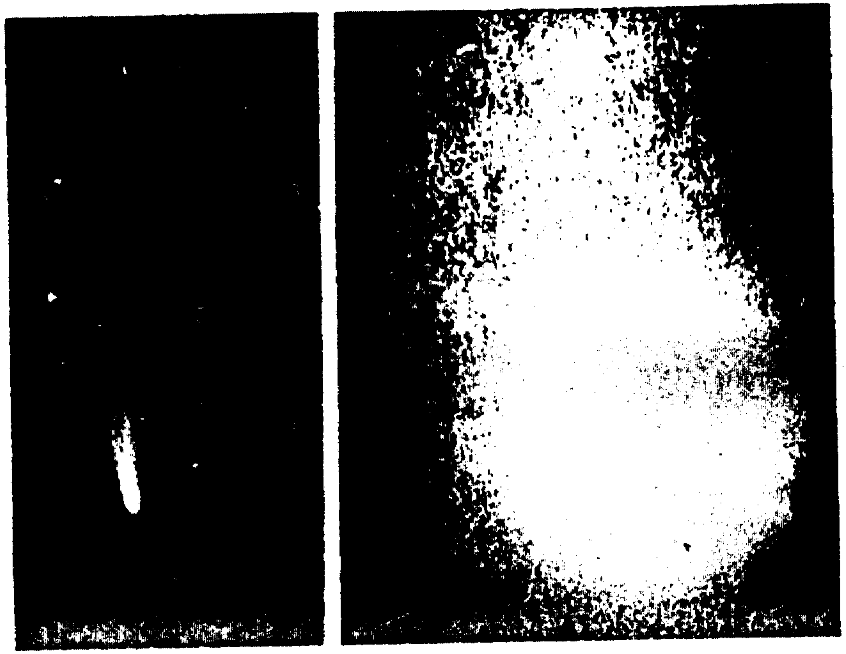

The extent of the H I Lyman-alpha envelope is seen on the right in the ultraviolet image of Comet Kohoutek 1973 XII obtained by an electrographic camera on board a sounding rocket on 8.1 January 1974 (Opal et al., *Science,* 185:702, 1974). For comparison, a visible image taken by a Nikon-F camera with an f/2.8, 180-mm lens on a similar rocket three days earlier (Feldman et al., *Science,* 185:705, 1974), is shown to the same scale on the left.

COMETS

Edited by
LAUREL L. WILKENING

With the assistance of
MILDRED SHAPLEY MATTHEWS

With 48 collaborating authors

(NASA-CR-169237) COMETS (Arizona Univ., Tucson.) 12 p HC A02/MF A01 CSCL 03B

N82-30210

Unclas
G3/91 30399

THE UNIVERSITY OF ARIZONA PRESS
TUCSON, ARIZONA

Mumma, M.J.; Cody, R.; and Schleicher, D. 1978. The cyanogen abundance of comets. *Bull. Amer. Astron. Soc.* 10:587 (abstract).
O'Dell, C.R. 1971. Spectrophotometry of Comet 1969g (T-S-K). *Astrophys. J.* 164:511-520.
Robinson, L.B., and Wampler, E.J. 1972. The Lick Observatory image-dissector scanner. *Publ. Astron. Soc. Pacific* 84:161-166.
Schleicher, D.G., and A'Hearn, M.F. 1981. Fluorescence of OH in comets. Submitted to *Astrophys. J.*
Sivaraman, K.R.; Babu, G.S.D.; Bappu, M.K.V.; and Parthasarathy, M. 1979. Emission band and continuum photometry of Comet West (1975n) I. Heliocentric dependence of the flux in the emission bands and the continuum. *Mon. Not. Roy. Astron. Soc.* 189:897-906.
Smith, A.M.; Stecher, T.P.; and Casswell, L. 1980. Production of carbon, sulfur, and CS in Comet West. *Astrophys. J.* 242:402-410.
Spinrad, H., and Stauffer, J. 1981. The production rates of [OI] in recent comets. *Icarus.* In press.
Spinrad, H.; Stauffer, J.; and Newburn, R.L. 1979. Optical spectrophotometry of Comet Tempel 2 far from the Sun. *Publ. Astron. Soc. Pacific* 91:707-711.
Stauffer, J.R., and Spinrad, H. 1981. The behavior of the red nuclear continuum of P/comets with varying heliocentric distance. *Icarus.* In press.
Stokes, G.M. 1972. The scattered light continuum of Comet Bennett 1969i. *Astrophys. J.* 177:829-834.
Swings, P. 1962. Comportement des raies interdites de l'oxygene dans les comètes. *Ann. d'Astrophys.* 25:165-170.
Stawikowski, A., and Greenstein, J.L. 1964. The isotope ratio C^{12}/C^{13} in a comet. *Astrophys. J.* 140:1280-1291.
Tatum, J.B., and Gillespie, M.I. 1977. The cyanogen abundance of comets. *Astrophys. J.* 218:569-572.
Tull, R.G. 1972. The Coudé spectrograph and echelle scanner of the 2.7 m telescope at McDonald Observatory. In *Auxiliary Instrumentation for Large Telescopes*, eds. S. Laustsen and A. Reiz (Geneva: ESO-CERN), pp. 259-274.
Vanýsek, V., and Rahe, J. 1978. The $^{12}C/^{13}C$ isotope ratio in comets, stars and interstellar matter. *Moon and Planets* 18:441-446.
Weaver, H.A.; Feldman, P.D.; Festou, M.C.; and A'Hearn, M.F. 1981. Water production models for Comet Bradfield (1979 X). *Astrophys. J.* In press.
Weissman, P.R. 1978. Observations of a near-extinct cometary nucleus. *Bull. Amer. Astron. Soc.* 10:588 (abstract).
Woszczyk, A. 1970. Le spectre cometaire dans le regions λ3884-3914 e. 4180-4752 Å. *Studie Soc. Sci. Torunensis* 4:267-291 (= Nr. 6, pp. 23-47 = *Bull. Astron. Obs. Torun* 46).
Wyckoff, S., and Wehinger, P.A. 1976. Molecular ions in comet tails. *Astrophys. J.* 204:604-615.
Wyller, A.A. 1962. C_2 Phillips bands in emission from Comet Candy (1960n)? *Observatory* 82:73-75.

ULTRAVIOLET SPECTROSCOPY OF COMAE

P.D. FELDMAN
The Johns Hopkins University

Vacuum ultraviolet observations from sounding rockets and satellite observatories of the gaseous comae of several recent comets are reviewed. The earliest of these led to discovery of the hydrogen envelope extending for millions of km from the nucleus. Subsequent observations of H I Lyman α, the OH (0,0) band and the oxygen resonance triplet have provided strong evidence for the water-ice model of the cometary nucleus. Several new species were discovered in the coma, including C, C^+, CO, S and CS. High-resolution spectroscopy and the spatial variation of the observed emissions provide means to elucidate the production and excitation mechanisms of these species. The similarity of the spectra of the half-dozen comets observed to date argues for a common, homogeneous composition (with the exception of dust and CO) of the cometary ice and a minimal effect on the neutral species due to molecular collisions in the inner coma.

Observations of comets in the vacuum ultraviolet have contributed since 1970 to significant progress in understanding cometary comae and the cometary nucleus itself. The first ultraviolet observations, of comets Tago-Sato-Kosaka 1969 IX and Bennett 1970 II, made in 1970 by both Orbiting Astronomical Observatory-2 (OAO-2) and Orbiting Geophysical Observatory-5 (OGO-5), demonstrated the existence of a hydrogen envelope that extended millions of km from the comet's nucleus (Bertaux et al. 1973; Code et al. 1972). Analysis of this H I Lyman-α envelope and the accompanying strong

emission from OH at 3085 Å (seen only weakly in groundbased spectra) provided strong confirmation of Whipple's icy conglomerate model proposed two decades earlier (Whipple 1950,1951) on the basis of the noncentral force perturbations of cometary orbits. The observed emissions could be accounted for by photodissociation by sunlight of H_2O evaporated from the surface of the "dirty snowball" nucleus; the derived H_2O production rate, typically on the order of 10^{29} to 10^{30} mol s^{-1}, was exactly the magnitude predicted by Whipple's model (Bertaux et al. 1973; Keller and Lillie 1974). Comet Tago-Sato-Kosaka was also observed in Lyman-α by a rocket experiment (Jenkins and Wingert 1972).

The next opportunity for vacuum ultraviolet observations came with Comet Kohoutek 1973 XII, discovered 10 months before perihelion, whose promise motivated an extensive campaign of coordinated space and ground-based observations. Atomic oxygen and carbon were discovered in the ultraviolet spectra obtained by two rocket experiments (Feldman et al. 1974; Opal and Carruthers 1977a) and direct Lyman-α images of the hydrogen envelope were obtained with rocket (Opal et al. 1974) and Skylab (Carruthers et al. 1974) ultraviolet cameras. The full potential of Comet Kohoutek 1973 XII was realized two years later with Comet West 1976 VI when rocket instrumentation developed for the Kohoutek observations was able to obtain the first comprehensive ultraviolet spectrum of a comet (Feldman and Brune 1976; Smith et al. 1980). The OAO-3 (Copernicus) observatory was used to obtain very high resolution line profiles of the H I Lyman-α emission from Comet West and several other comets (Festou et al. 1979) during this time period.

Since January 1978, the International Ultraviolet Explorer (IUE) satellite observatory has been available for cometary observations and while to date there have been no new comets of the intrinsic brightness of comets Bennett or West, this telescope in Earth orbit has permitted extensive observations of recent comets. Both comets Seargent 1978 XV (Jackson et al. 1979) and Bradfield 1979 X (Feldman et al. 1980) were moderately active comets; the latter was the first comet for which ultraviolet observations were made over a wide range of heliocentric distances, from 0.71 AU to 1.55 AU (Weaver et al. 1981a). Subsequently, several faint comets including P/Encke, P/Tuttle and P/Stephan-Oterma were observed by IUE (Weaver et al. 1981b) and provided a new data base for comparing composition and elucidating physical and chemical processes in the coma dependent on heliocentric distance and gas production rate.

I. THE ULTRAVIOLET SPECTRUM OF A COMET

The earliest results on the ultraviolet observations of comets and their interpretation, with an emphasis on H I Lyman-α emission, were reviewed by Keller (1976). Since that review, the sensitivity of solar-ultraviolet excited

TABLE I

List of Known Species from Rocket Observations of Comet West

Observed Species	Wavelength (Å)
H I	1216
O I	1304
C I	1561, 1657
C I (^{1}D)	1931
S I	1814
C II	1335
CO	1510
C_2	2313
CS	2576
OH	3085
CO^+	2200
CO_2^+	2890
Upper Limits	
H_2	1608
CO_2	1993
NO	2150

fluorescence in a cometary atmosphere was strikingly demonstrated by the rocket observations of Comet West (Feldman and Brune 1976; Smith et al. 1980) by which several species previously not observed in comets were detected and significant upper limits for several others were obtained. A list of known species is given in Table I. The IUE observations of comets Seargent 1978 XV and Bradfield 1979 X did not contribute to this list though the data from Comet Bradfield on the spatial distribution of CS emission point to CS_2 as the most probable short-lived parent molecule (Jackson et al. 1981). While H_2O is not directly observable in emission, its three dissociation products H, OH, and O are all detectable in the ultraviolet. In contrast, the neutral species seen in the visible spectrum (e.g., CN, NH, C_2, and C_3) are all highly reactive radicals derived from still unknown parent molecules whose abundance in the coma is $<1\%$ that of H_2O. The identification of the $\Delta v = 0$ sequence of Mulliken bands of C_2 near 2313 Å in the spectrum of Comet Bradfield (A'Hearn and Feldman 1980) provides a convenient way to correlate the satellite ultraviolet with visible observations.

Surprisingly, the ultraviolet spectra of all comets observed to date are remarkably similar, despite differences in visual appearance, dust/gas ratio,

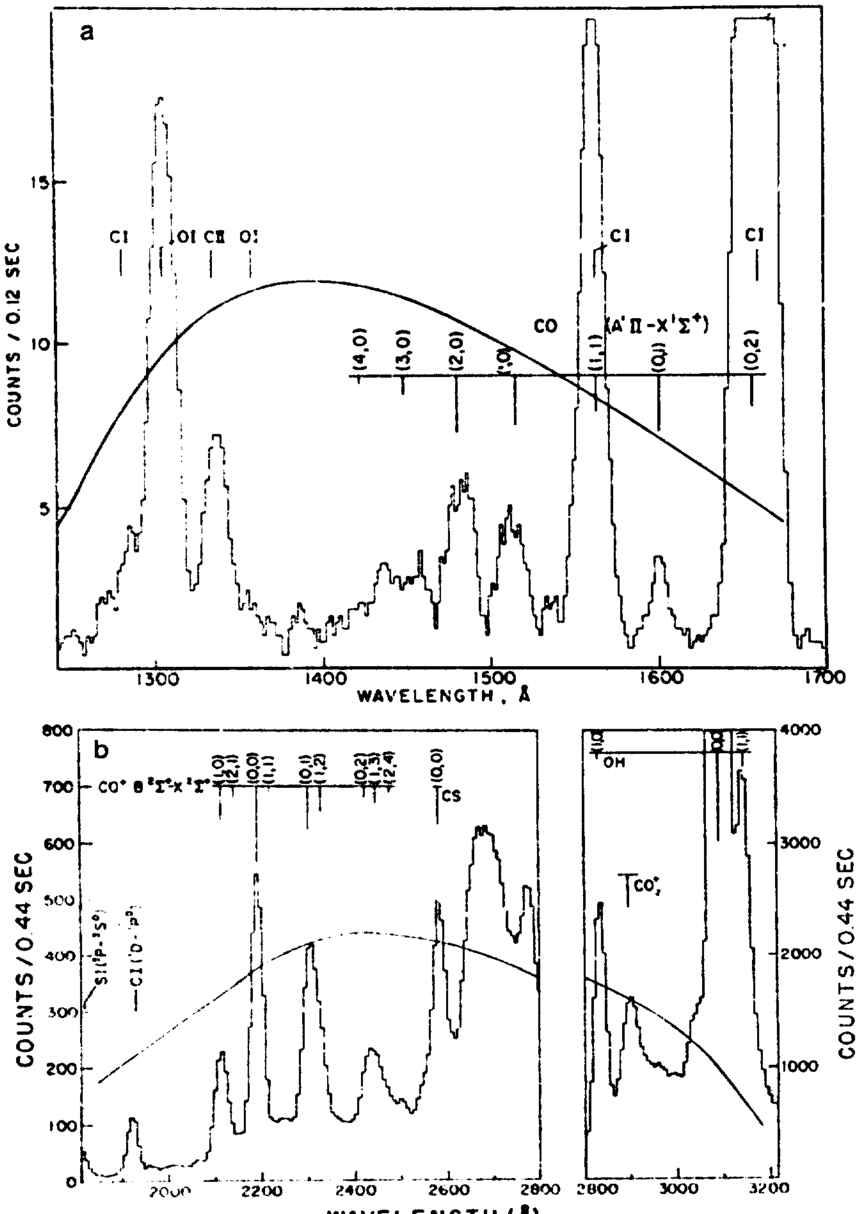

Fig. 1. Ultraviolet spectra of Comet West 1976 VI recorded by sounding rocket instruments on 5 March 1976 (Feldman and Brune 1976). (a) and (b) are short and long wavelength spectra respectively. In (a) a CaF_2 filter was used to attenuate the transmission of HI Lyman α to prevent grating scattered light from masking the weaker emission features.

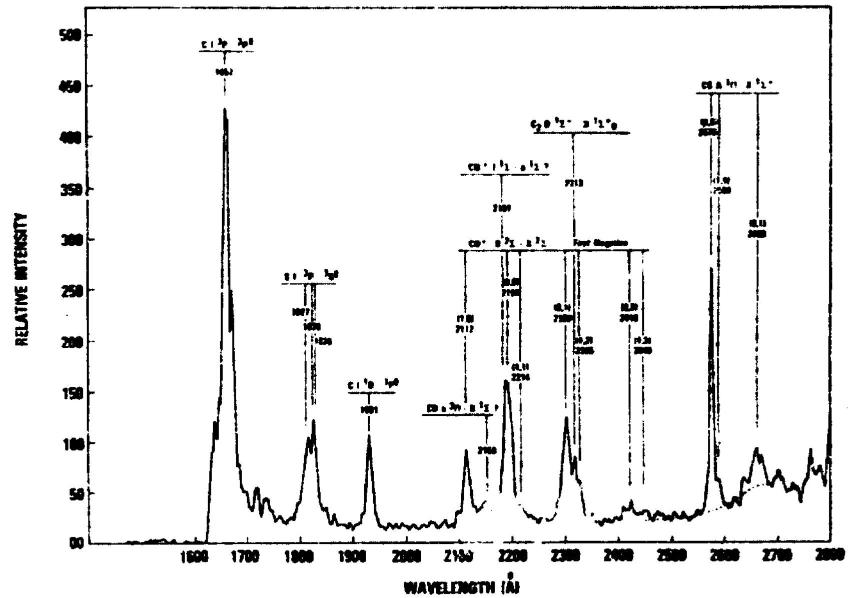

Fig. 2. Objective grating spectrum of Comet West obtained from a rocket launch on 10 March 1976 (Smith et al. 1980).

gas production rate, heliocentric distance and observing geometry. Besides the dust, only the CO^+ abundance appears to vary significantly from one comet to another. The similarity lends further support to the idea of common, homogeneous composition and possibly common origin for most comets. Furthermore, the similarity also suggests that chemical reactions in the inner coma are relatively insignificant in affecting the abundances of observed species largely determined by the photochemistry of the parent species that is evaporated from the cometary nucleus. The data from Comet Bradfield indicate that only the production of metastable $C(^1D)$ atoms (the lower level of the λ1931 Å transition) is dependent on inner coma chemistry, probably dissociative recombination of CO^+ ions (Feldman 1978).

Examples of ultraviolet spectra of several comets are shown in Figs. 1 through 5. The rocket spectra of Comet West 1976 VI on 5 March 1976 when the comet was 0.385 AU from the Sun, by Feldman and Brune (1976), are shown in Fig. 1. The short wavelength spectrum has been corrected for atmospheric O_2 absorption, and the relative intensities of the CO fourth positive bands agree much better with expected intensities for resonance fluorescence of sunlight than the published spectrum which included several spectral scans at low altitude that distorted the spectrum due to differential O_2 absorption in the Schumann-Runge bands. The projected slit area at the comet was $1.8 \times 10^5 \times 1.28 \times 10^6$ km^2 for the long wavelength spectrometer and

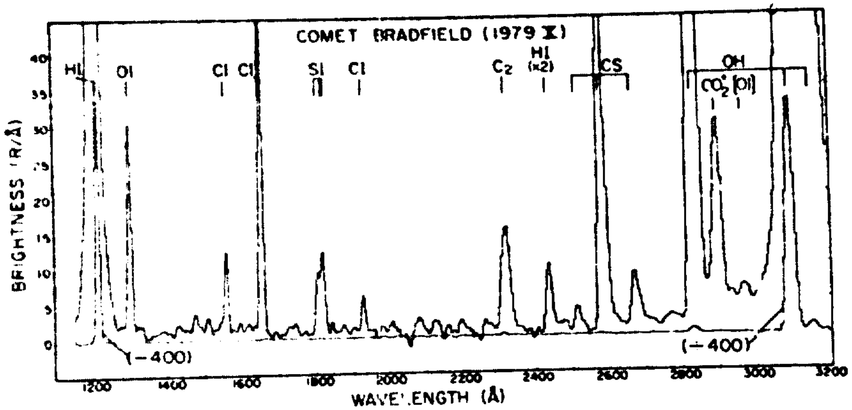

Fig. 3. Composite IUE spectrum of Comet Bradfield 1979 X. The observational parameters for Figs. 3, 4, and 5 are given in Table II.

$3.7 \times 10^5 \times 1.28 \times 10^6$ km^2 for the short wavelength spectrometer. Spectral resolution was 22 Å and 15 Å, respectively. The spectrum obtained five days later at $r = 0.52$ AU, by Smith et al. (1980), is shown in Fig. 2. The instrument used in this rocket experiment was an objective grating spectrograph with spectral resolution 7 Å permitting definitive identification of the CS(0,0) band at 2576 Å and the S I triplet at 1807, 1820 and 1826 Å. The spatial resolution of these data was ≈ 80,000 km, and indicated a nearly pointlike source for the CS emission.

IUE spectra of comets Bradfield 1979 X, Seargent 1978 XV and P/Encke are shown in Figs. 3, 4 and 5. Heliocentric and geocentric distance and projected area of the 10 X 20 arcsec slit for each observation are given in Table II. The spatial resolution, corresponding to 5 arcsec, is also given. Note the similarity of all three spectra, which differ mainly in relative brightness of O I λ 1304 which depends strongly on heliocentric velocity ($\dot{r}$). These spectra are also quite similar to that of Comet West shown in Figs. 1 and 2, except that the CO^+ first negative bands in the region 2100-2400 Å are absent. The two features present in this region are the C_2 Mulliken bands mentioned above and H I Lyman-α in second order. The absence of the CO^+ first negative bands so prominent in the spectrum of Comet West is consistent with the absence of weakness of the CO^+ comet-tail bands in visible spectra of these comets. The absence of these bands is more puzzling considering the strength of the CO_2 emission at 2890 Å; this might result from the relatively small projected slit of the IUE spectrographs (A'Hearn and Feldman 1980). Note that in the spectra of all these comets, both H I Lyman α at 1216 Å and the OH (0,0) band near 3085 Å are more intense than any other spectral feature, partly due to the large abundance of H and OH in the coma and partly to the large resonance scattering fluorescence efficiencies or g-factors for these transitions.

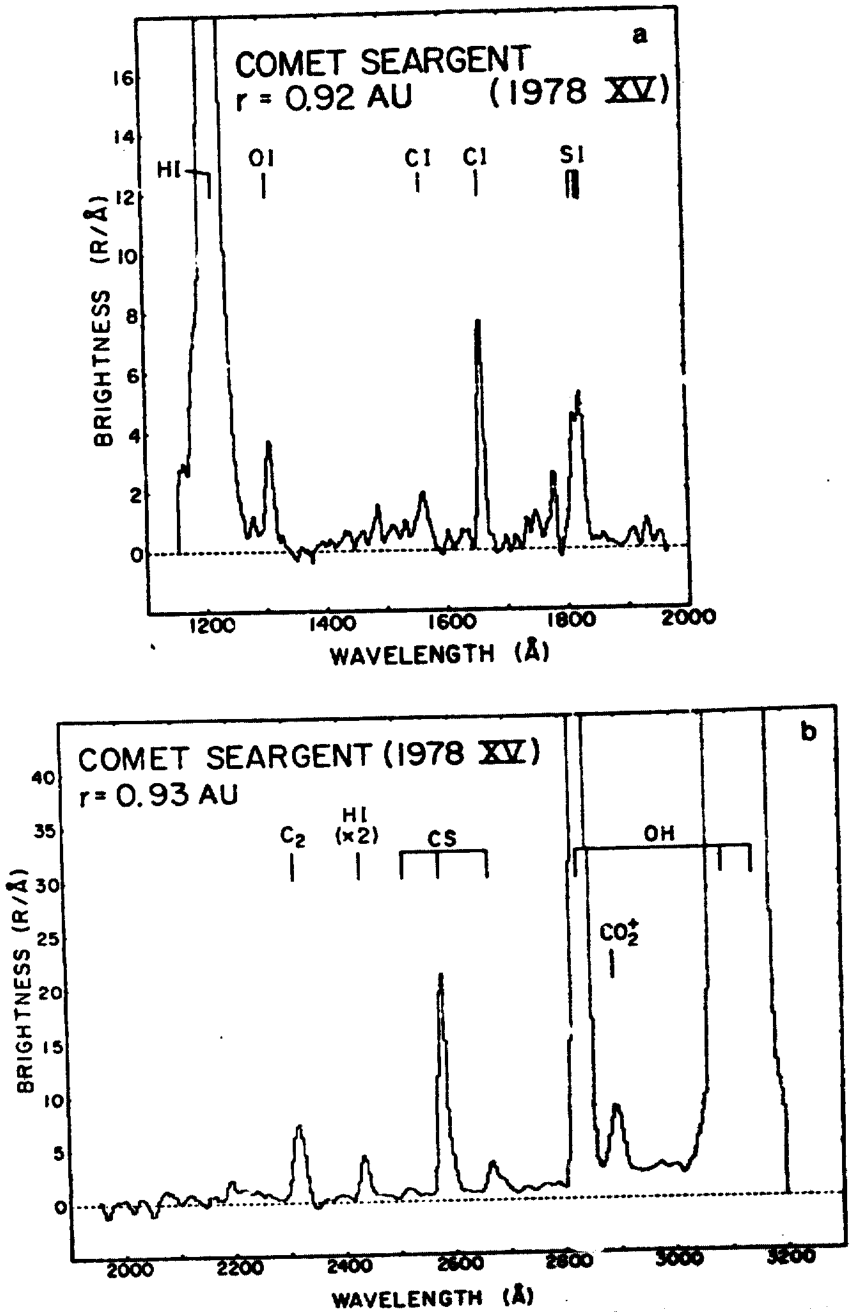

Fig. 4. IUE spectra of Comet Seargent 1978 XV. (a) and (b) are short and long wavelength spectra, respectively.

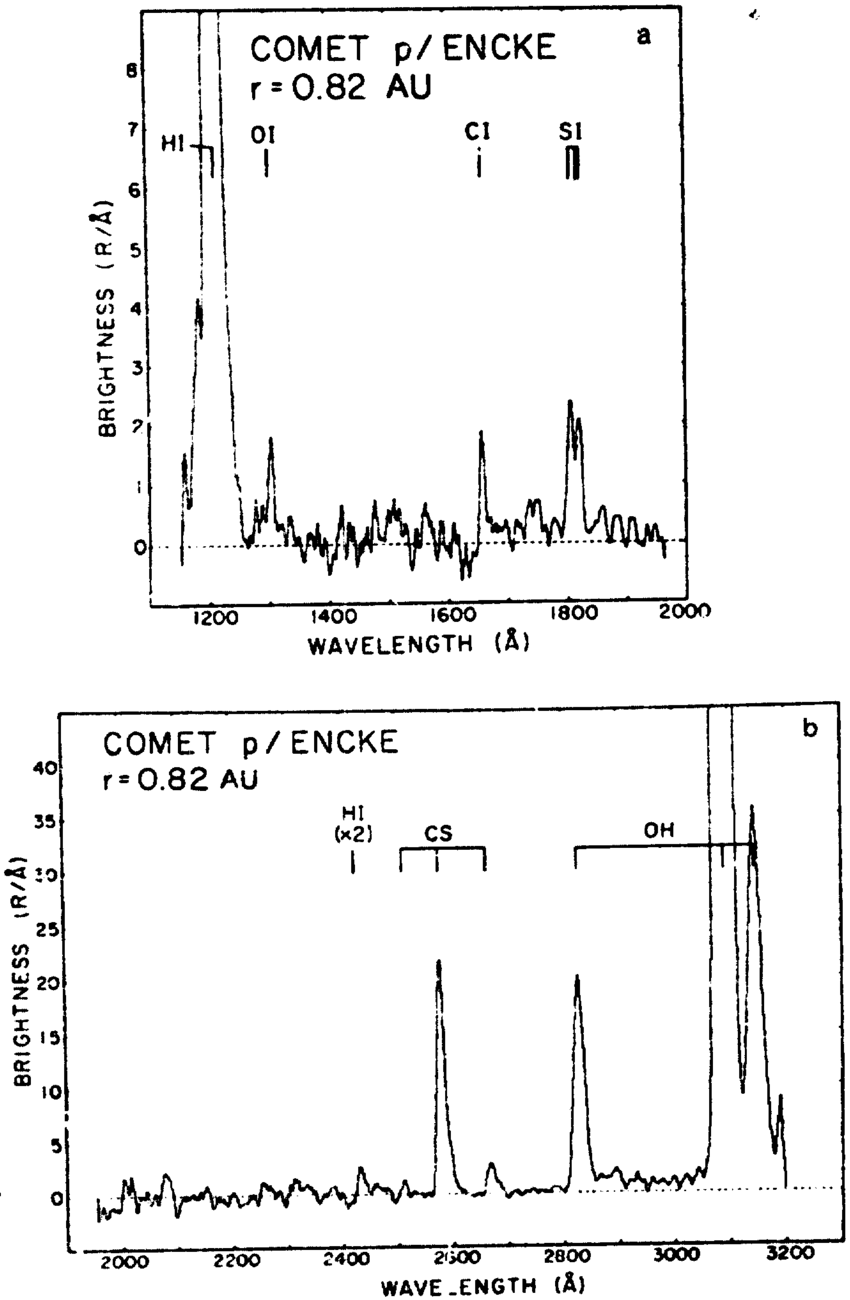

Fig. 5. IUE spectra of P/Encke. (a) and (b) are short and long wavelength spectra, respectively.

TABLE II

Observational Parameters for Figs. 3, 4, and 5

	Comet Bradfield 1979 X	Comet Seargent 1978 XV	Comet P/Encke
Observation Date	10 Jan. 1980	19 Oct. 1978	4 Nov. 1980
Heliocentric Distance (r in AU)	0.71	0.93	0.81
Geocentric Distance (Δ in AU)	0.615	0.76	0.32
Projected Slit Area (km^2)	4500 × 8900	5500 × 11000	2300 × 4600
Spatial Resolution (km)	2200	2800	1200

II. GAS PRODUCTION RATE

In addition to determining which species are present in the coma, a main goal of ultraviolet spectroscopy is to determine the rates at which these species are produced and their variation in response to changes in the solar stimulus. The method of finding the production rate from either surface brightness or total luminosity in a given spectral line is outlined briefly below.

It is generally accepted that almost all visible and ultraviolet emissions of a cometary coma are excited by resonance scattering or fluorescence of solar radiation. For an optically thin emission, the luminosity of the comet in this line or band is proportional to the total number of atoms or molecules in the coma, and the factor of proportionality is known as the g-factor usually expressed as the probability of scattering of a solar photon per unit time per molecule. The g-factor depends on the transition oscillator strength and solar flux. Note that in the ultraviolet below ~1700 Å the solar radiation is mainly line emission, so the Doppler shift due to the comet's heliocentric motion can produce large changes in the g-factor as the comet procedes in its orbit (Feldman et al. 1976). This is particularly important for the O I λ1304 emission, where for $\dot{r} > 30$ km s^{-1}, the cometary absorption wavelength is Doppler-shifted outside the solar linewidth and excitation of the oxygen resonance triplet procedes via fluorescent absorption of solar Lyman-β radiation. Figure 6 shows the g-factors for both resonance scattering and fluorescent excitation based on recent measurements of the solar O I λ1302 and Lyman-β fluxes and line shapes; both parameters are subject to variation during the course of a solar cycle (e.g., Mount et al. 1980). The C I λ1657 shows a much

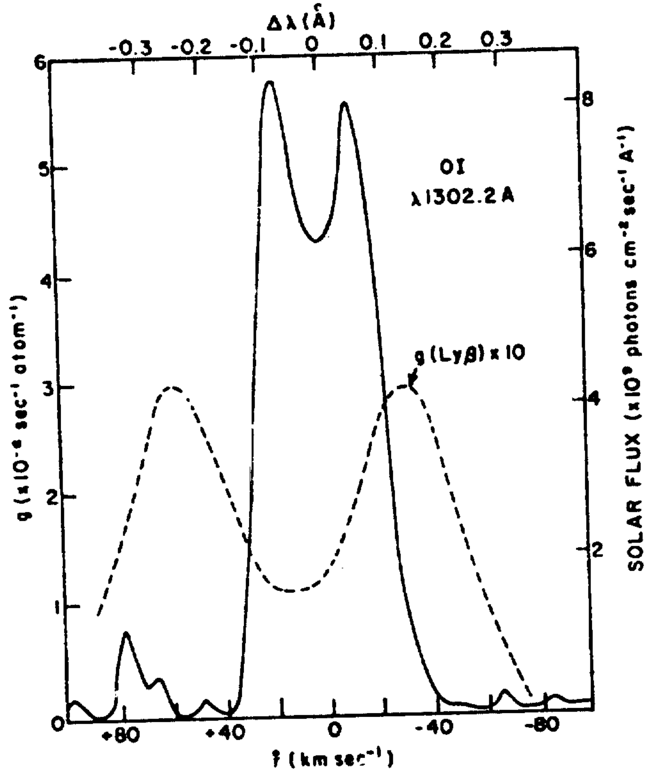

Fig. 6. The g-factor for O I λ1302 shown as a function of heliocentric velocity, with contributions from resonance scattering of solar O I λ1302 and fluorescent excitation by solar HI Lyman β (Feldman et al. 1976).

less drastic effect as the multiplet consists of six separated lines (Feldman et al. 1976). An additional effect, the Greenstein effect, (Greenstein 1958), arises from the differential velocities of atoms on the sunward and anti-sunward sides of the coma such that the effective g-factor varies across the cometary image. Evidence for such an effect in the O I λ1304 triplet in Comet Bradfield, where $\dot{r}$ shifted the solar line to the steep slope of the solar line profile, has been given by Weaver et al. (1981a).

At wavelengths ≥ 1700 Å where the solar spectrum is continuous with Fraunhofer absorption lines, variation in $\dot{r}$ produces the Swings effect, for example, in the OH(0,0) band at 3085 Å (Mies 1974). This can be seen from a comparison of IUE high dispersion spectra for comets Seargent ($\dot{r} \approx 35$ km s^{-1}) and Bradfield ($\dot{r} \approx 24$ km s^{-1}) (Schleicher and A'Hearn 1981), where the relative intensities of individual lines vary depending on coincidence of the absorption lines with Doppler-shifted absorption features in the solar spectrum. As a consequence, the g-factor for the band taken as a whole (as would be observed at low dispersion) also varies by almost a factor of five with $\dot{r}$,

ORIGINAL PAGE IS OF POOR QUALITY

but not in a regular way, and must be accounted for in derivation of gas production rates from observed brightness as described below. There are two other interesting consequences of this effect: the fluorescent pumping of the OH ground-state levels so that the 18 cm transitions can appear either in absorption or emission depending on $\dot{r}$ (Despois et al. 1981), and a variation in the OH lifetime with $\dot{r}$ (Jackson 1980) since the principal photodissociation of OH is through the strongly predissociating $v' \geq 2$ levels of the $A^1\Pi$ upper state. As yet, the Swings effect on the CS (0,0) band, the S I triplet, the CO^+ first negative bands, and the CO_2^+ bands at 2890 Å remains to be investigated. Also, the C II doublet at 1335 Å in Comet West observed by Feldman and Brune (1976) is not satisfactorily understood since resonance scattering by C^+ ions in the coma or tail does not seem possible due to the large heliocentric Doppler shift at the time of observation.

Thus, if the total flux F_i in a line of the ith species is measured, the production Q_i is given by

$$Q_i = \frac{4\pi\Delta^2 F_i}{g_i \tau_i} \tag{1}$$

where Δ is geocentric distance in cm, g_i is g-factor, and τ_i is lifetime of the species. Note that both g_i and τ_i depend on the solar flux which varies as r^{-2}, but that the product $g_i\tau_i$ is independent of r, and may be conveniently evaluated at 1 AU. Table III gives a list of current values of g-factors and lifetimes used in the interpretation of the observations. As noted above, the g-factors can vary strongly with heliocentric velocity and are also dependent on the solar flux. The largest uncertainty in the application of Eq. (1) is in the species lifetime, which is also a function of the solar cycle (Oppenheimer and Downey 1980).

For most cometary observations, particularly in the ultraviolet where the species lifetimes give scale lengths $\gtrsim 10^6$ km, the field of view is much smaller than the projected size of the coma and instead of the total flux an average surface brightness B_i is measured in Rayleighs

$$B_i = \bar{N} g_i \times 10^{-6} \tag{2}$$

where $\bar{N}_i$ is average column density of the species along the line of sight, which must be determined by integrating a suitable model of the density along a line of sight at a projected distance ρ from the nucleus to get $N_i(\rho)$ and then integrating over the instrumental field of view. The simplest model for species density assumes symmetrical radial outflow and exponential decay (Haser 1957,1966), and introduces another unknown parameter, the species outflow velocity. A description of this model and its extension to the second daughter product has been given by Festou (1981). The outflow velocity has been discussed by Mendis and Ip (1976) for the parent molecules and Festou (1981) and Feldman (1978), among others, for the various atomic fragments. In principle, spatial variation of brightness with ρ is sufficient to give only the

TABLE III

Lifetimes and g-factors at 1 AU (Quiet Sun)

Species	Emission Wavelength (Å)	g-factor $g(s^{-1})$	Lifetime $\tau(s)$
H I	1216	1.4×10^{-3} (a)	2.4×10^{6} (a)
O I	1302	$0.3\text{-}6 \times 10^{-6}$ (b)	1.4×10^{6} (c)
C I	1657	2.5×10^{-5} (b)	1.7×10^{6} (d)
S I	1813	7×10^{-5} (e)	10^{6} (e)
C I (^{1}D)	1931	1.2×10^{-4} (f)	3250 (f)(g)
CO	1510	2.2×10^{-7} (f)	1.4×10^{6} (d)
H_2	1608	1.6×10^{-7} (b)	9×10^{6} (h)
NO	2150	7.7×10^{-6} (j)	3×10^{5} (h)
CS	2575	7×10^{-4} (e)	10^{5} (e)
OH	3085	$2.5\text{-}10 \times 10^{-4}$ (k)	$0.7\text{-}2.1 \times 10^{5}$ (l)

(a) Opal and Carruthers (1977b); (b) Feldman et al. (1976); (c) Opal and Carruthers (1977a); (d) Feldman (1978); (e) Jackson et al. (1981); (f) Feldman and Brune (1976); (g) independent of r; (h) Huebner and Carpenter (1979); (j) Cravens (1977); (k) Schleicher and A'Hearn (1981); (l) Jackson (1980).

scale length $v_i\tau_i$ but with dissociation products of H_2O simultaneous observation of H, OH, and O should permit unique determination of both the velocity of the parent and the lifetimes of the daughter products.

The radial outflow model has several limitations. It is only valid for photodestruction products and does not allow for atoms produced by chemical reactions such as carbon by dissociative recombination of CO^+ (Feldman 1978). For hydrogen and oxygen it does not properly account for the spatial distribution resulting from excess velocities of fragment atoms. Festou (1981) has developed a vectorial model of H_2O dissociation and shown that the radial outflow model gives a close approximation to the exact OH brightness profile albeit with an underestimated daughter scale length. An additional difficulty in analyzing resonance scattering of atomic hydrogen and oxygen is that in moderately active comets the column abundances of these species are sufficiently high so that radiation entrapment is significant. However, treatment of the radiative transfer problem is difficult because the exact physical conditions in the gas coma are unknown. Also, the solar extreme ultraviolet fluxes that produce both resonance scattering of the atomic fragments and photodestruction of the parent molecules may vary by a factor of 2 to 4

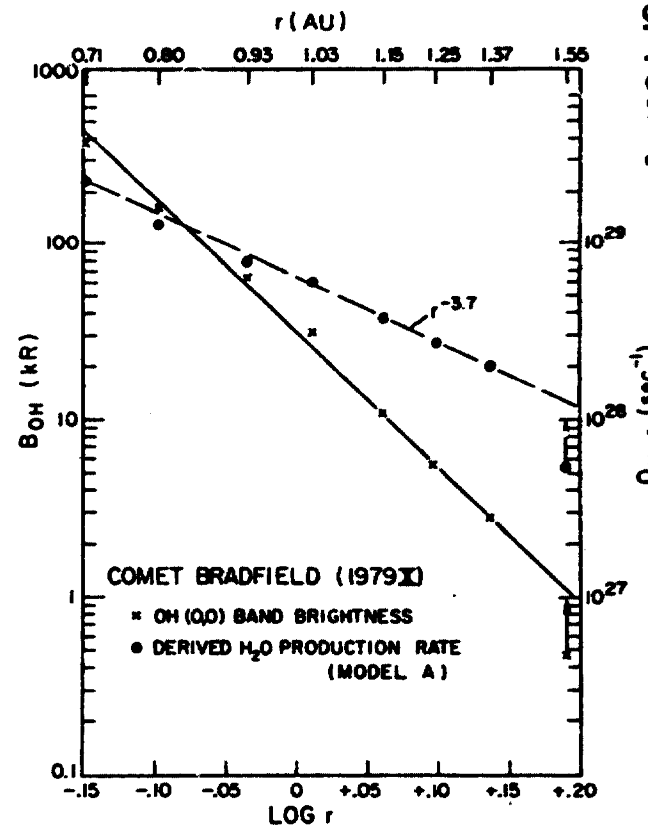

Fig. 7. Variation of the OH (0,0) band brightness and the derived H_2O production rate as a function of heliocentric distance for Comet Bradfield 1979 X (Weaver et al. 1981a).

during the solar cycle (Oppenheimer and Downey 1980). Nevertheless, in our preliminary analysis of HI Lyman-α, OI λ1302, and the OH (0,0) band the observed brightness is completely consistent with a water source (Weaver et al. 1981a).

III. EVOLUTION OF THE COMA

As noted above, the IUE observations of Comet Bradfield made over a wide range of heliocentric distance permit determination of the variation of water vaporization rate from the comet nucleus with time and distance from the Sun. Such data should prove useful for comparison with dirty ice models of the nucleus. The data, the brightness of the OH (0,0) band at 3085 Å averaged over the central 10×15 arcsec of the spectrograph aperture, are shown in Fig. 7 along with the OH production rate (≈ 90% of the H_2O production

rate) derived by fitting the data to the predictions of a radial outflow model averaged over the aperture. The model used (A in the figure) assumed H_2O outflow velocity $v_{H_2O} = 1.0$ km s^{-1} and OH lifetime $\tau_{OH} = 5 \times 10^4$ s at 1 AU. The other parameters were the water lifetime $\tau_{H_2O} = 8.2 \times 10^4$ s at 1 AU and the OH outflow velocity $v_{OH} = 1.15$ km s^{-1}. However, a different value of v_{H_2O} can also provide a good fit to the spatial variation of the OH brightness if the OH lifetime is suitably adjusted; a model with $v_{H_2O} = 0.5$ km s^{-1} and $\tau_{OH} = 1 \times 10^5$ s gives a water production rate smaller by a factor of 2 than that shown in Fig. 7. The actual value is probably between these extremes.

The surprising result from Fig. 7 is the dependence of the water production rate on heliocentric distance which varies as $r^{-3.7}$. This disagrees with the widely held idea that the controlling influence on vaporization is the total solar energy input which varies only as r^{-2}. Previous OAO-2 results on comets Bennett and Tago-Sato-Kosaka (Keller and Lillie 1974,1978) were in basic agreement with the r^{-2} dependence, but the data covered a much narrower range of heliocentric distance. Detailed models by Delsemme (1973) of the evaporation of water from a bare nucleus give a variation of Q_{H_2O} proportional to r^{-n}, with n between 2.4 and 2.9 for a range of visible and infrared albedos. More recently, including effects of the dust coma in such models has led to prediction of an even steeper variation of water vaporization rate with heliocentric distance (P.R. Weissman and H.H. Kieffer, personal communication 1981), in qualitative agreement with the IUE results. Observations of additional comets over a similar range of r are needed to determine whether this behavior is typical of most comets.

IV. COMPARATIVE SPECTROSCOPY

The IUE observatory is capable of detecting and tracking comets whose visual magnitude is as faint as 10. Over its time in space it should permit observations of comets of different types and intrinsic magnitudes from which compositional and evolutionary trends can be studied. Since all observations are made with the same spectrographs uncertainties due to instrumental differences are eliminated. Moreover, by comparing spectra of different comets at the same heliocentric distance (1 AU, for example), the effects of other independent parameters like gas production rate and the consequent size of the collision zone in the inner coma might be detected. In the IUE spectra of Figs. 3 through 5, as well as that of P/Tuttle, the heliocentric velocity dependence of the O I λ1304 g-factor discussed above is clearly demonstrated (Weaver et al. 1981b).

As an example, the water production rates for six comets observed by IUE derived from analysis of the OH (0,0) band brightness using a consistent radial-outflow model at heliocentric distances of ~1 and 1.5 AU, are given in Table IV. Note that the range of production rates near 1 AU is relatively small, and that the comets whose perihelia lie near 1.5 AU, P/Stephan-Oterma and Meier 1980q, are more active than Comet Bradfield 1979 X at that heliocentric distance. The derived values of Q_{H_2O} appear well correlated with gas production rates derived from groundbased observations of C_2 and CN (Weaver et al. 1981b). For P/Encke, the water production rate is found to be several times higher than the value derived from the OGO-5 observations of H I Lyman-α during the 1970 apparition (Bertaux et al. 1973).

The effect of the 10 X 20 arcsec IUE spectrograph apertures is particularly severe for the CS and S I emissions which appear nearly pointlike at the 5 arcsec instrumental resolution of the spectrographs. Jackson et al. (1981) have demonstrated that this spatial variation is consistent with a common parent for these two species, CS_2, with photochemical lifetime 100 s at 1 AU. A comparison of the observed profile of the CS (0,0) band along the 20 arcsec dimension of the aperture with the expected profile, using a radial outflow model smoothed by instrumental resolution, is shown in Fig. 8. For such emissions, the observed brightness averaged over the slit is strongly dependent on the comet's geocentric distance. Using the model, the CS parent production rate was evaluated for the four comets in Table IV observed near 1 AU and found to be 5×10^{-4} of the water production rate, to within a factor of two, for all four comets (Weaver et al. 1981b). Although the statistical sample is too small to draw a conclusion for all comets, CS_2 certainly appears to exist in the same relative amount in the ice of these comets.

TABLE IV

Water Production Rates

Comet	Observation Date	Heliocentric Distance r (AU)	Geocentric Distance Δ (AU)	Production Rate Q_{H_2O} (10^{28} s^{-1})
Scargent 1978 XV	16 Oct. 1978	0.87	0.78	33
Bradfield 1979 X	31 Jan. 1980	1.03	0.29	5.1
P/Encke	24 Oct. 1980	1.01	0.29	0.96
P/Tuttle	7 Dec. 1980	1.02	0.50	6.2
Bradfield 1979 X	3 Mar. 1980	1.55	1.45	0.5-1.0
P/Stephan-Oterma	7 Dec. 1980	1.58	0.59	3.0
Meier 1980q	7 Dec. 1980	1.52	1.89	8.5

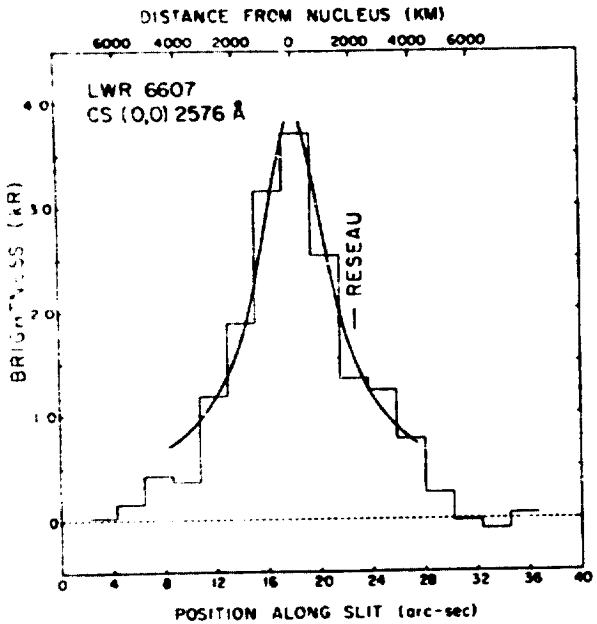

Fig. 8. Variation of the CS (0,0) band brightness in the large aperture of the IUE spectrograph. The smooth lines indicate expected response if the CS was produced by photodissociation of a parent molecule whose lifetime at 1 AU is ~ 100 s (Jackson et al. 1981).

ORIGINAL PAGE IS
OF POOR QUALITY

V. LYMAN-α OBSERVATIONS

An extensive review of the H I Lyman-α observations of comets Bennett 1970 II and Kohoutek 1973 XII and their interpretation was given by Keller (1976). The syndyname model of Keller and Meier (1976) assuming two outflow velocity components (depending on whether the H parent is H_2O or OH) gave an excellent fit to the extensive wide-field Lyman-α images of Comet Kohoutek (Meier et al. 1976). The only other comet for which a direct Lyman-α image was obtained was Comet West (Opal and Carruthers 1977b), but in this case the syndyname model was unable to reproduce the observed isophotes; the most likely source of the discrepancy was conjectured to be irregular gas production related to splitting of the nucleus (Keller and Meier 1980). Despite this problem, the presence of hydrogen in the coma with two different velocity distributions seems well established by the Copernicus observations of the Lyman-α line shape at different positions in the coma of Comet Kobayashi-Berger-Milon 1975 IX (Festou et al. 1979). Unfortunately, the IUE observations are not applicable to this problem.

VI. FUTURE DIRECTIONS

The cometary coma appears quite different in the vacuum ultraviolet from its visual image, both in form and photometric content. Only a handful of comets have been observed from above the Earth's atmosphere and the detailed information on numerous comets available to groundbased observers does not exist for the ultraviolet. However, results to date have clearly demonstrated the importance of ultraviolet observations to understanding cometary phenomena. IUE continues to operate well and will provide an enlarged data base as more comets are observed; hopefully a comet similar to comets Bennett or West will appear during its lifetime. The Space Telescope (ST) to be launched in 1985 will continue to provide ultraviolet spectroscopy and imaging from Earth orbit, although its use in cometary observations will be limited by the small fields of view of the spectrographs and the expected heavy demand for ST observing time. Space Shuttle and Spacelab will provide an additional platform for cometary ultraviolet observations; several instruments now being developed should be available for flight during the 1985-86 apparition of Comet P/Halley. Among these is a 90-cm telescope/spectrograph currently in the definition study phase at Johns Hopkins University which will be sensitive at wavelengths as short as 500 Å, permitting the detection of He I λ584 if helium is present in the coma. Improved instrumentation with higher sensitivity and spectral and spatial resolution should make possible the study of collision processes in the inner coma. The detection of the Lyman-α line of deuterium displaced 0.3 Å from H I Lyman α and currently limited by instrumentally scattered H I Lyman α remains the ultimate challenge to the cometary spectroscopist.

Acknowledgments: The author acknowledges fruitful collaboration on many of the topics discussed above with H.A. Weaver, M.C. Festou and M.F. A'Hearn. The IUE observatory staff have been extremely generous in accommodating their observing schedule to the random apparitions of comets during 1980 and in providing the expertise to track these fast-moving objects. This work was supported by grants from the National Aeronautics and Space Administration.

REFERENCES

A'Hearn, M.F., and Feldman, P.D. 1980. Carbon in Comet Bradfield 1979l. *Astrophys. J.* 242:L187-L190.
Bertaux, J.L.; Blamont, J.E.; and Festou, M. 1973. Interpretation of hydrogen Lyman-alpha observations of Comets Bennett and Encke. *Astron. Astrophys.* 25:415-430.
Carruthers, G.R.; Opal, C.B.; Page, T.L.; Meier, R.R.; and Prinz, D.K. 1974. Lyman-α imagery of Comet Kohoutek. *Icarus* 23:526-537.
Code, A.D.; Houck, T.E.; and Lillie, C.F. 1972. Ultraviolet observations of comets. In *The Scientific Results from Orbiting Astronomical Observatory (OAO-2)*, ed. A.D. Code, (Washington, D.C.: NASA SP-310), pp. 109-114.

Cravens, T.E. 1977. Nitric oxide gamma band emission rate factor. *Planet. Space Sci.* 25:369-372.

Delsemme, A.H. 1973. The brightness law of comets. *Astrophys. Letters* 14:163-167.

Despois, D.; Gerard, E.; Crovisier, J.; and Kazès, I. 1981. The OH radical in comets: Observation and analysis of the hyperfine microwave transitions at 1667 MHz and 1665 MHz. *Astron. Astrophys.* 99:320-340.

Feldman, P.D. 1978. A model of carbon production in a cometary coma. *Astron. Astrophys.* 70:547-553.

Feldman, P.D., and Brune, W.H. 1976. Carbon production in Comet West (1975n). *Astrophys. J.* 209:L145-L148.

Feldman, P.D.; Opal C.B.; Meier, R.R.; and Nicolas, K.R. 1976. Far ultraviolet excitation processes in comets. In *The Study of Comets*, eds. B. Donn, M. Mumma, W. Jackson, M. A'Hearn, and R. Harrington, (Washington, D.C.: NASA SP-393), pp. 773-795.

Feldman, P.D.; Takacs, P.Z.; Fastie, W.G.; and Donn, B. 1974. Rocket ultraviolet spectrophotometry of Comet Kohoutek (1973f). *Science* 185:705-707.

Feldman, P.D.; Weaver, H.A.; Festou, M.C.; A'Hearn, M.F.; Jackson, W.M.; Donn, B.; Rahe, J.; Smith, A.M.; and Benvenuti, P. 1980. IUE observations of the UV spectrum of Comet Bradfield. *Nature* 286:132-135.

Festou, M. 1981. The density distribution of neutral compounds in cometary atmospheres. I. Models and equations. *Astron. Astrophys.* 95:69-79.

Festou, M.; Jenkins, E.B.; Keller, H.U.; Barker, E.S.; Bertaux, J.L.; Drake, J.F.; and Upson, W.L. 1979. Lyman-alpha observations of Comet Kobayashi-Berger-Milon (1975 IX) with *Copernicus*. *Astrophys. J.* 232:318-328.

Greenstein, J.L. 1958. High-resolution spectra of Comet Mrkos (1957d). *Astrophys. J.* 128:106-113.

Haser, L. 1957. Distribution d'intensite dans la tête d'une comète. *Bull. Acad. Roy. Belgique*, Classe des Sciences 43:740-750.

Haser, L. 1966. Calcul de distribution d'intensité relative dans une tête cométaire. *Cong. Coll. Univ. Liège* 37:233-241.

Huebner, W.F., and Carpenter, C.W. 1979. Solar photo rate coefficients. *Los Alamos Report* LA-8085-MS.

Jackson, W.M. 1980. The lifetime of the OH radical in comets at 1 AU. *Icarus* 41:147-152.

Jackson, W.M.; Halpern, J.; Feldman, P.D.; and Rahe, J. 1981. Production of CS and S in Comet Bradfield (1979 X). Submitted to *Astron. Astrophys.*

Jackson, W.M.; Rahe, J.; Donn, B.; Smith, A.M.; Keller, H.U.; Benvenuti, P.; Delsemme, A.H.; and Owen, T. 1979. The ultraviolet spectrum of Comet Seargent 1978m. *Astron. Astrophys.* 73:L7-L9.

Keller, H.U. 1976. The interpretation of ultraviolet observations of comets. *Space Sci. Rev.* 18:641-684.

Keller, H.U., and Lillie, C.F. 1974. The scale length of OH and the production rates of H and OH in Comet Bennett (1970 II). *Astron. Astrophys.* 34:187-196.

Keller, H.U., and Lillie, C.F. 1978. Hydrogen and hydroxyl production rates of Comet Tago-Sato-Kosaka (1969 IX). *Astron. Astrophys.* 62:143-147.

Keller, H.U., and Meier, R.R. 1976. A cometary hydrogen model for arbitrary observational geometry. *Astron. Astrophys.* 52:272-281.

Keller, H.U., and Meier, R.R. 1980. On the $L\alpha$ isophotes of Comet West (1976 VI). *Astron. Astrophys.* 81:210-214.

Meier, R.R.; Opal, C.B.; Keller, H.U.; Page, T.L.; and Carruthers, G.R. 1976. Hydrogen production rates from Lyman-α images of Comet Kohoutek (1973 XII). *Astron. Astrophys.* 52:283-290.

Mendis, D.A., and Ip, W.-H. 1976. The neutral atmospheres of comets. *Astrophys. Space Sci.* 39:335-385.

Mies, F.H. 1974. Ultraviolet fluorescent pumping of OH 18-centimeter radiation in comets. *Astrophys. J.* 191:L145-L148.

Mount, G.H.; Rottman, G.J.; and Timothy, J.G. 1980. The solar spectral irradiance 1200-2550 Å at solar maximum. *J. Geophys. Res.* 85:4271-4274.

Opal, C.B., and Carruthers, G.R. 1977a. Carbon and oxygen production rates for Comet Kohoutek (1973 XII). *Astrophys. J.* 211:294-299.

Opal, C.B., and Carruthers, G.R. 1977b. Lyman-alpha observations of Comet West (1975n). *Icarus* 31:503-509.

Opal, C.B.; Carruthers, G.R.; Prinz, D.K.; and Meier, R.R. 1974. Comet Kohoutek: Ultraviolet images and spectrograms. *Science* 185:702-705.

Oppenheimer, M., and Downey, C.J. 1980. The effect of solar-cycle ultraviolet flux variations on cometary gas. *Astrophys. J.* 241:L123-L127.

Schleicher, D.G., and A'Hearn, M.F. 1981. OH fluorescence in comets. Submitted to *Astrophys. J.*

Smith, A.M.; Stecher, T.P.; and Casswell, L. 1980. Production of carbon, sulfur and CS in Comet West. *Astrophys. J.* 242:402-410.

Weaver, H.A.; Feldman, P.D.; Festou, M.C.; and A'Hearn, M.F. 1981a. Water production models for Comet Bradfield (1979 X). *Astrophys. J.* in press.

Weaver, H.A.; Feldman, P.D.; Festou, M.C.; A'Hearn, M.F.; and Keller, H.U. 1981b. Observations of faint comets with IUE. Submitted to *Icarus*.

Whipple, F.L. 1950. A comet model. I. The acceleration of Comet Encke. *Astrophys. J.* 111:375-394.

Whipple, F.L. 1951. A comet model. II. Physical relations for comets and meteors. *Astrophys. J.* 113:464-474.

W. Wisniewski, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.
J.A. Wood, Harvard College Observatory, Center for Astrophysics, Cambridge, MA.
I. Wright, University of Cambridge, Cambridge, England.
*S. Wyckoff, Department of Physics, Arizona State University, Tempe, AZ.
D.K. Yeomans, Jet Propulsion Laboratory, Pasadena, CA.
S. Yngvesson, Electrical Engineering Department, University of Massachusetts, Amherst, MA.
D.T. Young, Physikalisches Institut, Bern Universität, Bern, Switzerland.
B.H. Zellner, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ.
R.H. Zerull, Bereich Extraterrestrische Physik, Ruhr-Universität Bochum, Bochum, West Germany.

The editor acknowledges the support of NASA Grant NASW-3413 and NSF Grant AST-8010829. The following authors wish to acknowledge specific funds involved in supporting the preparation of their chapters.

A'Hearn, M.F.; NASA Grant NSG-7322
Brownlee, D.E.; NASA Grant NSG-9052
Campins, H.; JPL Contract BP-724887 and NASA Grant NSG-7114
Degewij, J.; JPL NASA Grant NAS7-100
Delsemme, A.H.; NSF Grant AST-80-18919 and NASA Grant NSG-7381
Elphic, R.C.; UCLA NASA Contract NAS2-9491 and JPL NASA Contract NAS7-100
Feldman, P.D.; NASA Grants NGR 21-001-001 and NSG-5393
Fink, U.; NASA Grants GSFC 71-7 (13 and 15) and NSG-7070
Fraundorf, P.; NASA Grant NGL-26-008-067
Hanner, M.S.; JPL Contract BP-724887 and NASA Grant NSG-7114
Jackson, W.M.; NASA Grant NSG-5071
Kamoun, P.G.; NSF Grant PHY78-07760 and NASA Grant NGR 22-002-672
Luhmann, J.G.; UCLA NASA Contract NAS2-9491 and JPL NASA Contract NAS7-100
Neugebauer, M.; UCLA NASA Contract NAS2-9491 and JPL NASA Contract NAS7-100
Ney, E.P.; NASA Grant NSG-2014
Pettengill, G.H.; NSF Grant PHY78-07760 and NASA Grant NGR 22-002-672
Russell, C.T.; UCLA NASA Contract NAS2-9491 and JPL NASA Contract NAS7-100
Sekanina, Z.; NASA Contract NAS7-100
Shapiro, I.I.; NSF Grant PHY78-07760 and NASA Grant NGR 22-002-672
Tedesco, E.F.; JPL NASA Grant NAS7-100
Walker, R.M.; NASA Grant NGL 26-008-067
Weissman, P.R.; NASA Contract NAS7-100
Whipple, F.L.; NASA Grant NSG-7082